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PYROLYSIS OF MUNICIPAL AND INDUSTRIAL WASTE

by

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ABSTRACT

This Paper provides a Historical Overview of some 21 U.S. research and development activities associated with municipal/industrial waste and biomass conversion-to-energy pyrolysis technologies. The History begins in the early 1970's and is brought forward to the present. Of the 21 pyrolysis processes/projects discussed, 19 were sponsored by the U.S. Government (7 by their Environmental Protection Agency and 12 by their Department of Energy) and 2 were developed by industry. Five pyrolysis demonstration plants are described, as are one prototype-scale effort, 6 pilot-scale projects, 8 bench-scale activities, and the plans for one commercial plant soon to be constructed.

PYROLYSIS OF MUNICIPAL AND INDUSTRIAL WASTE

INTRODUCTION

In man's everyday activities, large volumes of organic solid wastes are generated. These wastes are generated in the home, in commercial establishments and throughout the Nation's varied industrial operations. Over the years, relatively little attention has been paid to the final disposition or utilization of these wastes. Due to this lack of attention, many environmental insults resulted from the disposal of these wastes, insults such as open-burning, leaching dumps, and improper discharges to surface and groundwaters. These insults led to the initial passage in the United States (U.S.) of the 1965 Solid Waste Disposal Act, followed by the 1970 and 1976 Resource Recovery Acts and their subsequent Amendments. These Acts mandated the Federal Government (EPA and its predecessor Agencies) to support research and demonstrations to develop and apply new or improved technologies for recovering materials and energy from solid wastes. This mandate, coupled with the U.S. Department of Energy's (DOE's) concern over our dwindling energy supply, has focused our Nation's attention on the utilization of these wastes as sources of energy. Many options to utilize these wastes as energy resources have been investigated. Options have varied from combustion in waterwall or mass-burning incinerators, to co-firing of prepared wastes with coal in industrial boilers, to the thermochemical or pyrolytic conversion of these wastes into usable fuel products.[1]

Pyrolysis is, of course, the thermal conversion of organic feedstocks to recoverable energy products (such as fuel gas, fuel oil and char); the endothermic pyrolytic reactions are carried out in a reactor in the near-absence of oxygen which allows the organics to be converted to other organics suitable for fuel or to synthesis gases or oils suitable for subsequent upgrading to feedstocks for chemicals manufacture.

This Paper is intended to provide a historical perspective relative to past and current U.S. efforts to develop processes which feature the pyrolytic conversion of solid wastes or biomass into usable energy forms. Past R, D & D (research, development and demonstration) efforts will be briefly described so as to provide some background for the description of the current activities which will follow. European and Japanese efforts in the pyrolysis area have not been described herein, however their activities have been substantial as well.[2-5]

EARLY U.S. ATTEMPTS AT PYROLYSIS DEMONSTRATION PLANTS (1970-1981)

In the U.S., the enactment of the Solid Waste Disposal Act of 1965 and the Resource Recovery Act of 1970 provided EPA with funds allocated for large-scale demonstration grants for waste conversion technology development. Three pyrolysis projects/processes were selected by EPA for funding in the early 1970's; they were: (1) The Monsanto Landgard Process, (2) The Andco-Torrax Process, and (3) The Occidental Liquefaction Process. In addition, Union Carbide Corporation developed their Purox® Process with their own corporate funds.[4] And, in the late 1970's, DOE commissioned the building of a demonstration plant in Albany, Oregon to test their Biomass Catalytic Liquefaction Process.6 Each of these early efforts will be described below.

The Monsanto Landgard Process

In 1972, an EPA demonstration grant was awarded to the City of Baltimore, Maryland to help fund a 1000 ton-per-day (TPD) demonstration of the Monsanto Landgard Process. It employed a rotary kiln pyrolyzer into which shredded municipal solid waste (MSW) was fed at one end and air and auxiliary fuel for combustion at the other end. Hot fuel products of combustion contacted the MSW, and pyrolysis gases and char were formed. The pyrolysis gases passed on to an afterburner and were subsequently used for steam production.[7] The plant started up in 1975 but was beset with operational difficulties (refractory failures, failure to meet Maryland's air pollution regulations, etc); Monsanto eventually withdrew from the project in 1977. Baltimore has since converted the system to a 550 TPD mass-burning incinerator.[4]

The Andco-Torrax Process

In approximately 1970, another EPA demonstration grant was awarded to Erie County, New York to allow for the partial funding of a 75 TPD demonstration of the Andco-Torrax Process in Orchard Park. This process used a vertical "slagging" pyrolyzer to convert incoming MSW to a fuel gas and a slag which exited out the bottom of the reactor. Figure 1 is a schematic of the reactor utilized.[4,8] Demonstration tests continued until 1977 when it was shut down and later dismantled. Commercial facilities were built by Andco-Torrax between 1976 and 1979 in Luedellange, Luxembourg (200 TPD), Grasse, France (170 TPD), Frankfurt, West Germany (200 TPD) and Creteil France (200 TPD). Two other demonstration-size plants were built: One for DOE at the Disney World amusement park in Orlando, Florida (100 TPD) and one in Hamamatsu, Japan (87 TPD).[4]

The Occidental Liquefaction Process

In 1972, work began under the joint sponsorship of EPA and San Diego County on the development of the Garrett Pyrolysis Process, later known as the Occidental Liquefaction Process. A 4 TPD pilot plant led to a 200 TPD demonstration plant, funded in about 1975 and constructed by 1977. Figure 2 is a schematic of this process.[7] The objective was to separate out the inorganics from the MSW feed and then to convert the minus 14 to 24 mesh organic fraction (via a low-temperature, entrained-bed pyrolyzer) to a highly-oxygenated (33 weight percent oxygen) fuel oil having a heating value of about 115,000 Btu/gallon.[4,7] The heat required for the endothermic pyrolysis reactions was provided by the combustion of the off-gas and a fraction of the char produced.[7] The plant was shut down in about 1978 after only limited sustained runs because of the many operational problems that were encountered (such as aerosols in the recycle-gas compressor).[4]

The Union Carbide Purox® Process

In the early 1970's, the Union Carbide Corporation began development of the Purox® (Waste Pyrolysis) Process. An early schematic of the process is shown in Figure 3. A 5 TPD pilot plant began operation in Tonawanda, New York in 1971 and a 200 TPD demonstration unit was started-up in 1974.[7,8]

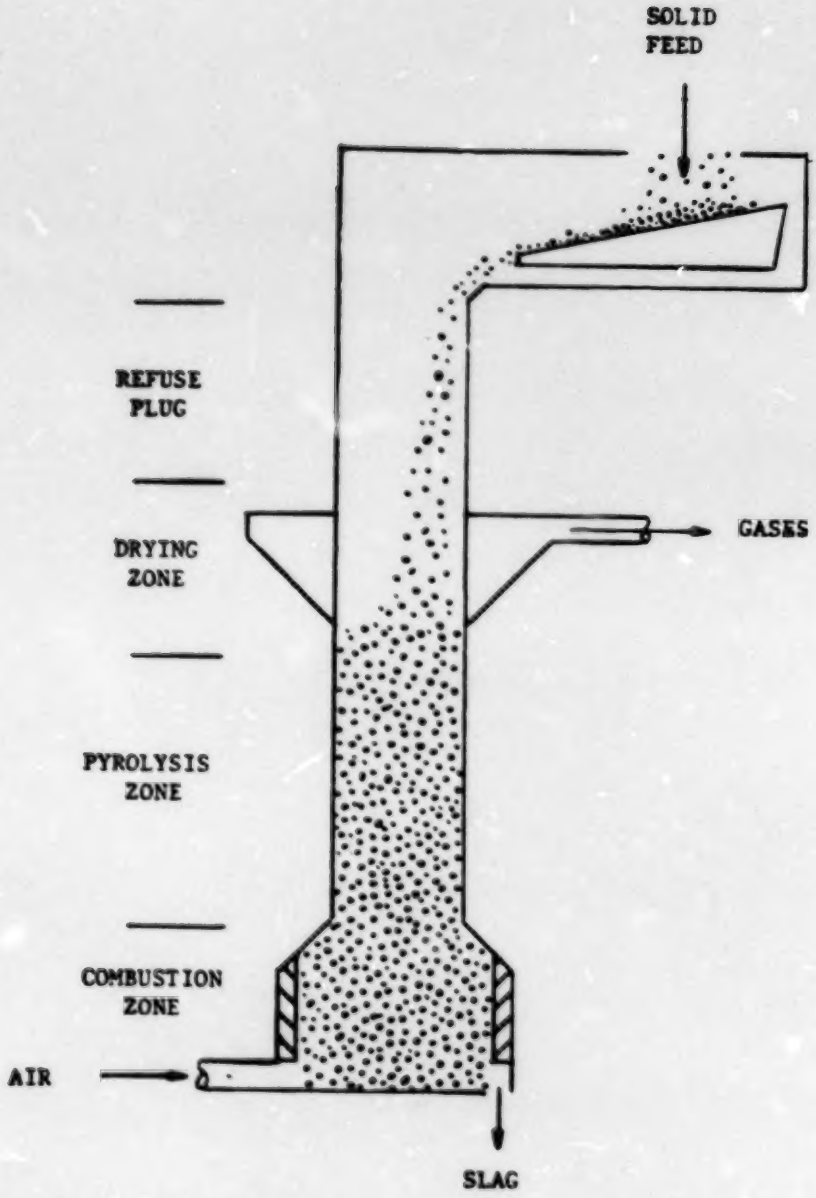

Figure 1. Schematic of the Andco-Torrax Reactor

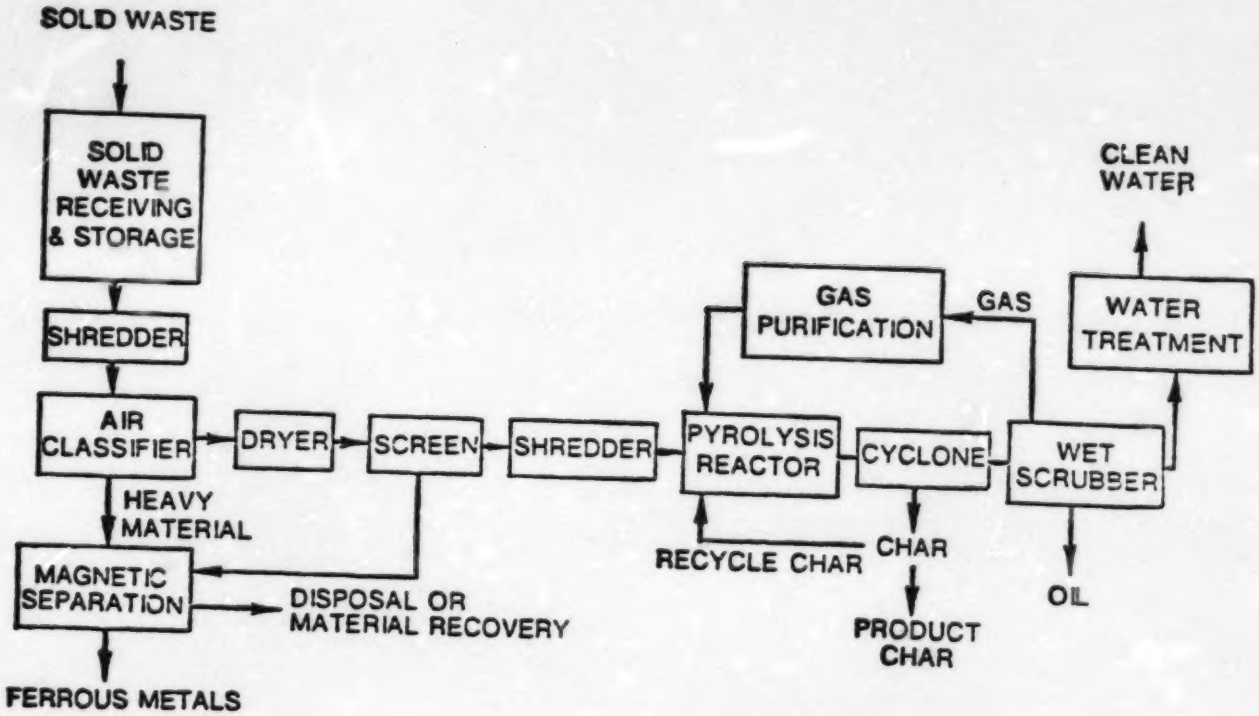

Figure 2. Occidental Liquefaction Process

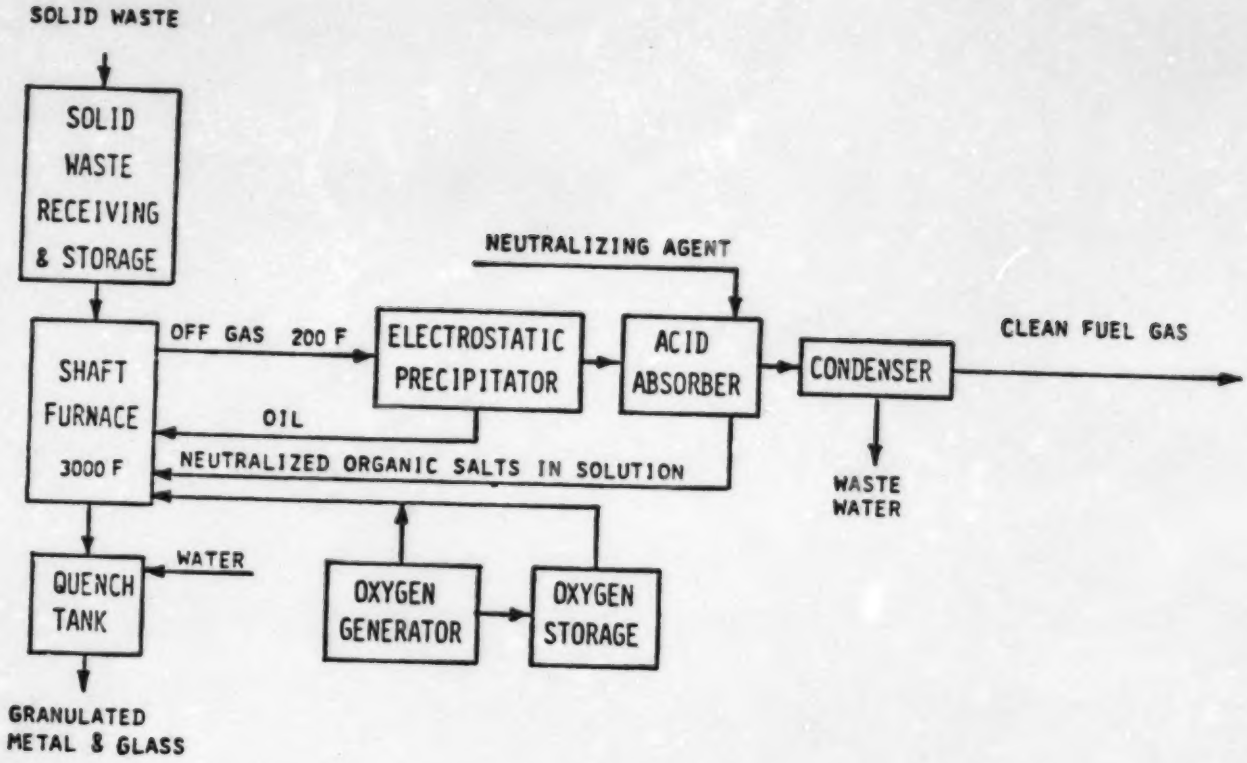

Figure 3. Union Carbide Purox® Process

The process used a shaft furnace to pyrolyze the incoming, downward-flowing MSW. "Pure" (about 95 percent) oxygen entered the bottom of the reactor and combusted a fraction of the waste to provide the heat necessary for the pyrolysis.[7] Since little nitrogen entered the system, the product gas had a higher heating value than that from most pyrolysis processes (about 300 to 390 Btu/scf).[4] About 0.2 tons of oxygen were typically used for each ton of solid waste fed to the process.[4,7] The demonstration plant is now idle. The reactor and the ram feeding system were licensed to Showa Denko K.K., who built a 150 TPD unit for MSW conversion to fuel gas in Chichibu, Japan. That unit was started-up in 1981.[4]

DOE's Biomass Catalytic Liquefaction Process

In the late 1970's, a research/demonstration facility was built by the U.S. Department of Energy in Albany, Oregon to test their Biomass Catalytic Liquefaction Process. In this process, a biomass feedstock (typically, an agricultural industry one) was mixed with recycled wood oil, a Na_2CO_3 catalyst, and a H_2/CO reducing gas and then injected into a 3000 psi reaction vessel heated to about 350°C.[6] The product stream was cooled and flashed into a pressure let-down vessel. The oil product was withdrawn and a part of it was recycled as a slurry medium. There was an aqueous slurry version of the process as well, and both versions were tested in 1980-1981. Technical feasibility was shown for both versions, however, the results indicated that neither version was economically competitive at that time (due partially to the large oil recycle requirement). Consequently, the Albany facility was deactivated in 1981.[6]

RESEARCH DONE BY EPA AIMED AT "GOING BACK TO THE BASICS" (1975-1980)

Because of the general lack of success at the demonstration plant scale, EPA (who was then still charged with the Federal responsibility for developing better waste-to-energy processes) decided to begin afresh, at the bench and pilot scales, with a more deliberate approach regarding the development of processes for the pyrolytic conversion of solid waste to fuel gas or synthesis gas, fuel oil and/or char. They accomplished this by carrying out bench-scale research at Princeton University, at the China Lake Naval Weapons Center and some concurrent pilot-scale research at the Energy Resources Company (ERCO). The latter project led to the near-demonstration of the "Mobile Pyrolysis Process." Each of these research endeavors will be discussed briefly below.

Princeton University's Steam Gasification Research

EPA funded Princeton University to investigate the effects of residence time, temperature, and heating rate on the pyrolytic reactions taking place during the steam gasification of organic wastes. It was found that pyrolytic volatile matter cracks very rapidly in the gas phase at temperatures above 650°C to yield a hydrocarbon-rich synthesis gas. At temperatures above 700°C, the rates of ethylene formation were second only to those of carbon monoxide in magnitude. Consequently, Princeton felt that organic waste materials would be an excellent, low-priced feedstock for olefin production.

Figure 4 shows the olefinic hydrocarbon gas production (of ethylene and propylene) versus residence time for the various gas phase temperatures studied in Princeton's bench-scale reactor system.[9]

China Lake's Waste-to-Gasoline Research

EPA also sponsored bench-scale research at the China Lake (California) Naval Weapons Center aimed at converting waste into a polymer gasoline product. The process featured the selective pyrolysis of organic wastes to gases rich in ethylene and propylene. The pyrolysis gases would then be compressed and purified (by having the CO_2 scrubbed out), producing a by-product fuel gas stream (containing H_2, CH_4 and CO) and a reactive hydrocarbon stream containing the ethylene and propylene. This last stream would then be further compressed and sent to a non-catalytic polymerization reactor operating at perhaps 750 psig and 450°C where high-octane gasoline was formed. Based on the experimentation performed, it was projected that about 68 gallons of polymer gasoline and 8 gallons of lubricating-like oil could be produced from each ton of municipal solid waste (MSW) treated by this process. Figure 5 shows the high degree of conversion to "C_2^+" material (those hydrocarbons heavier than the methanes) possible in a pyrolysis reactor operating at various temperatures and various pyrolysis gas partial pressures (expressed as "concentration" or grams of dry "ECO II" commercially-prepared MSW fuel/cubic meter of inert carrier gas).[10]

ERCO's Pilot-Scale Fluidized Bed Pyrolysis Research

The most comprehensive pyrolysis research directed by EPA in this time period was carried out by the Energy Resources Company (ERCO) in Cambridge, Massachusetts. A 20-inch diameter fluidized bed pyrolysis reactor was constructed and tested using many different organic feedstocks (feedstocks like paper, sewage sludge, corncobs, MSW, various industrial wastes such as waste oil, tires, plastics and wood chips, and mixtures of some of them). Five major variables were studied, as to their effect on the final reaction products; these were: temperature, fluidization velocity, feed rate, bed height and particle size. Some 345 test runs were reported upon; illustrative of these, Table 1 presents data on the pyrolysis of MSW at different temperatures, oxygen concentrations, and fluidization velocities and shows the resultant impact of these on the mass and energy yields of gas, oil and char (and on the mass yield of water).[11]

ERCO's Near-Development of a Prototype-Scale "Mobile Pyrolysis System"

Together with the State of California's Solid Waste Management Board, EPA funded the construction of a 100 TPD fluidized bed Mobile Pyrolyzer which was intended to travel around the State converting such feedstocks as rice straw and lumbermill and cotton gin wastes to transportable fuels such as pyrolytic oil and pyrolytic char. Any fuel gas that was to be produced would be used to provide the process heat and electrical needs for the two-trailer unit when it was located at one of the 12 sites that it was to visit in its first year of operation. Figure 6 presents a material balance for the situation where the 150 Btu/scf fuel gas would have been used to

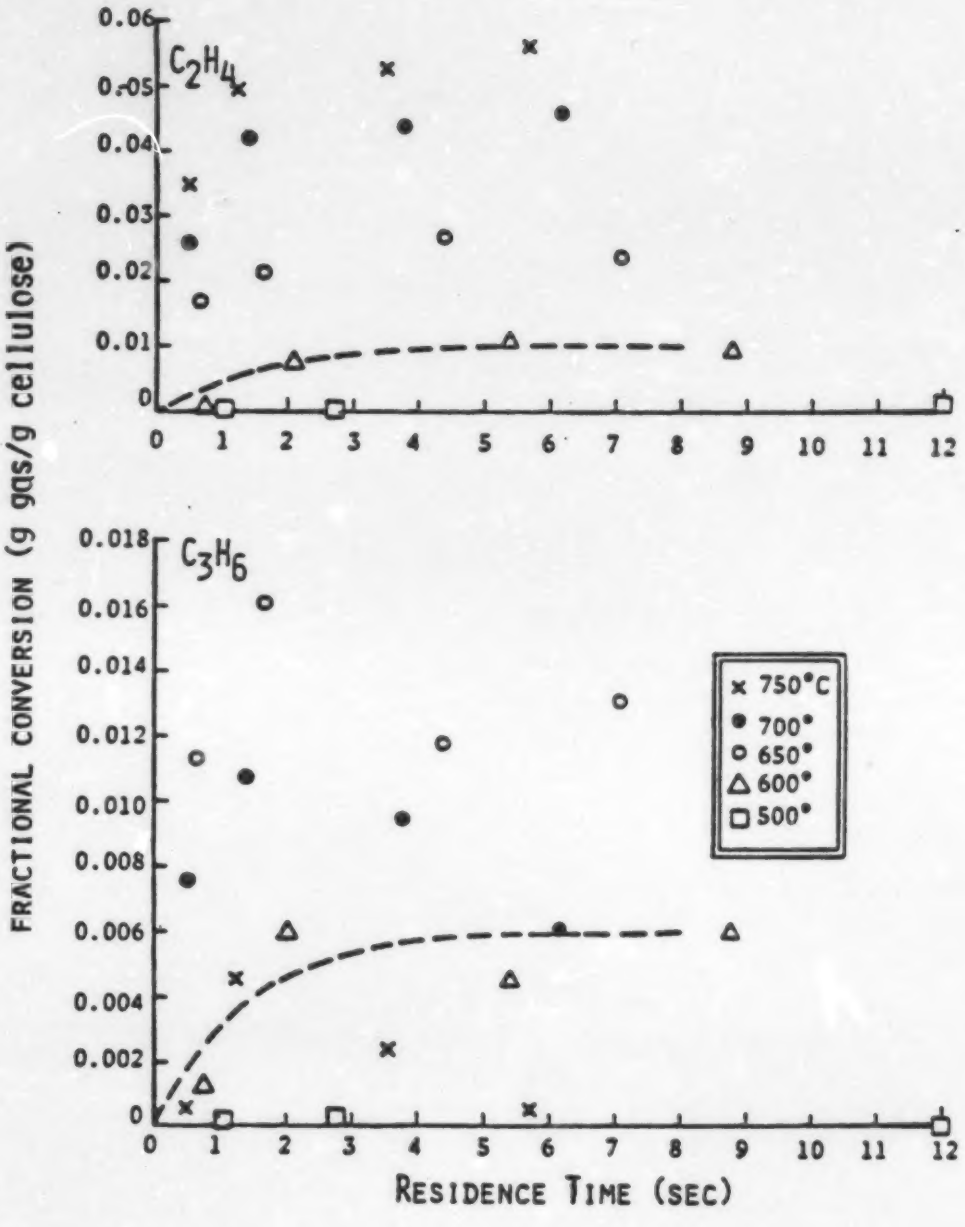

Figure 4. Olefinic Hydrocarbon Gas Production vs. Residence Time for Various Gas Phase Temperatures (Princeton)

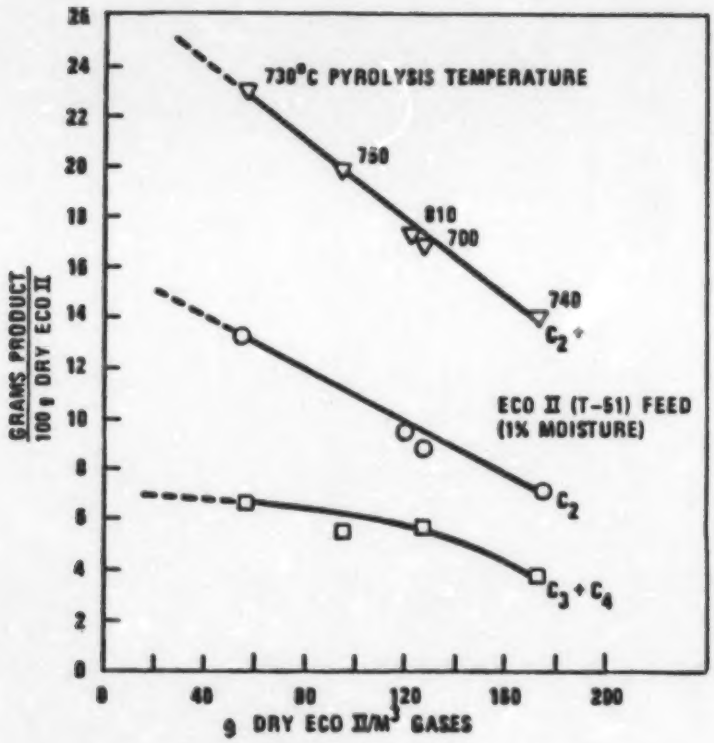

Figure 5. Products vs. Concentration in 6.1-meter Pyrolysis Reactor (China Lake)

TABLE 1. PYROLYSIS OF MUNICIPAL SOLID WASTE (FULL BED) [ERCO]

FILE NO.	TEMP C°	FEED RATE Kg/hr	FLUIDIZING GASES			BED HT. (m)	MATERIAL YIELD, %				ENERGY YIELD, %		
			FLUID. VEL. (m/s)	O_2%	H_2O%		GAS	OIL	CHAR	WATER	GAS	OIL	CHAR
8	550	28	0.40	0.17	19.5	0.6	27	10	24	40	5	16	25
14	760	39	0.36	0.17	19.5	0.6	48	4	15	33	33	7	16
1	610	100	0.39	0.34	19.4	0.6	23	11	27	39	10	17	29
5	710	159	0.39	0.43	19.3	0.6	36	6	24	34	25	10	25
3	750	155	0.42	0.17	19.5	0.6	39	5	18	39	28	7	19
16	800	83	0.37	0.21	19.5	0.6	53	3	13	31	38	5	14
12	810	103	0.41	0.34	19.4	0.6	51	2	13	34	37	3	14
6	490	30	0.46	0.09	19.6	0.6	22	12	21	44	3	19	22
9	550	33	0.54	0.17	19.5	0.6	30	13	20	38	9	20	21
15	645	42	0.47	0.43	19.3	0.6	46	4	16	34	29	6	17
11	800	57	0.72	0.60	19.1	0.6	56	3	12	29	35	4	13
7	510	63	0.49	0.68	19.1	0.6	16	17	19	48	4	27	21
2	730	135	0.44	0.17	19.5	0.6	34	25	13	28	22	40	13
4	760	107	0.63	0.17	19.5	0.6	40	5	16	39	28	8	17
17	825	69	0.54	0.43	19.3	0.6	57	3	14	26	40	4	15
19	870	58	0.56	0.09	19.6	0.6	55	1	15	29	37	2	16

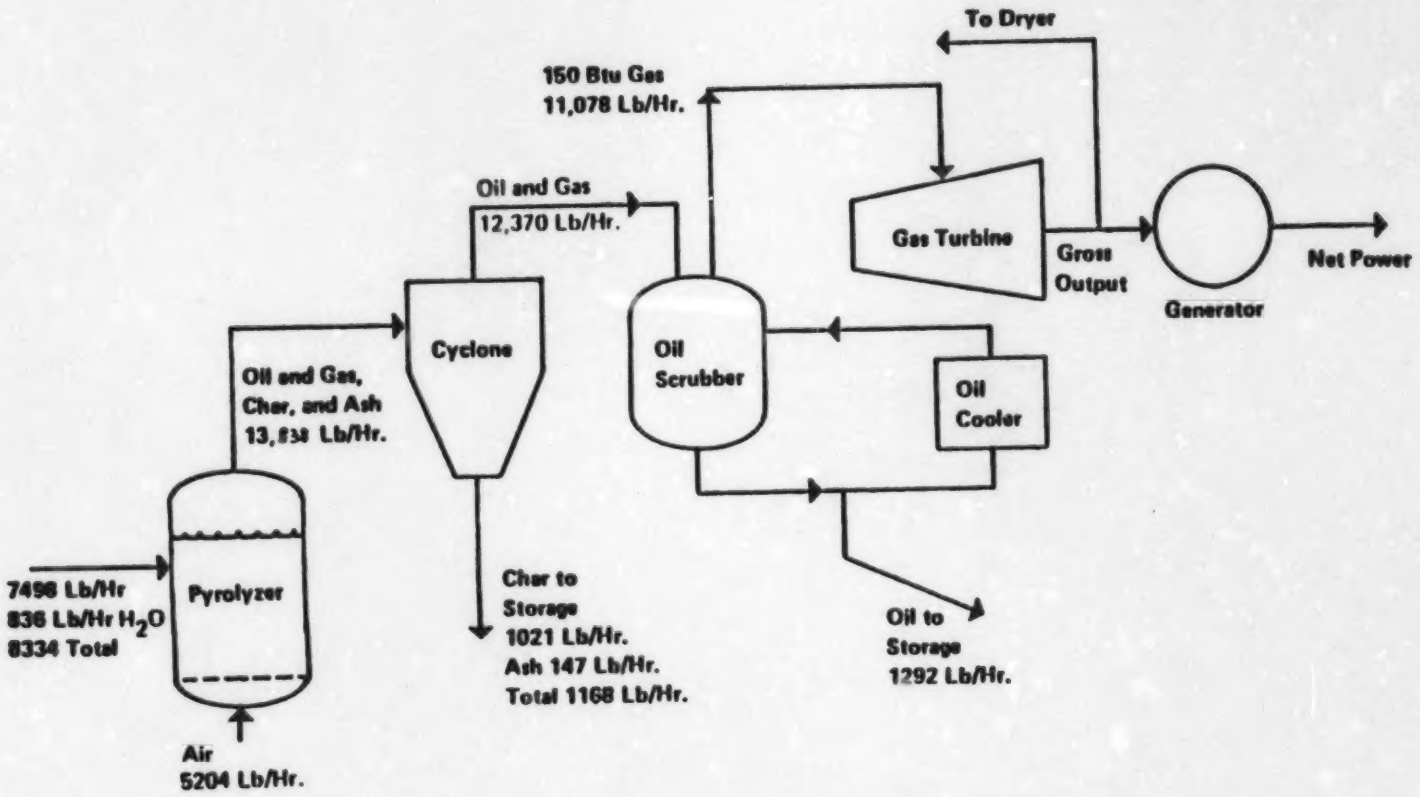

Figure 6. Material Balance for the Mobile Pyrolysis System (ERCO)

drive a gas turbine for on-trailer power needs.[12] Unfortunately, however, just as construction of the two-trailer system was nearing completion in early 1980, EPA had to withdraw its future funding support due to the shift in the then shared Federal responsibility for waste-to-energy research from EPA and the U.S. Department of Energy (DOE) to DOE alone. The demonstration of the Mobile Pyrolysis System was never able to be completed due to the State's eventual withdrawal of their support as well. After a hiatus of several years, process development in this general area of pyrolysis research (i.e., the fluidized bed area) was re-started by a private firm, Power Recovery Systems, Incorporated, also of Cambridge, Massachusetts. Their planned commercialization in this area will be discussed below (under "New Commercial Plants on the Horizon").

RESEARCH BEING DONE BY DOE (1980 - Present)

DOE continued EPA's general research approach of not proceeding to the demonstration stage too quickly, i.e., not before most of a process' design and operational difficulties had been worked out at the pilot scale. Consequently, they too initiated a program of bench- and pilot-scale research on waste and biomass pyrolysis technologies. Some of these DOE research activities will be highlighted below to give an appreciation of the breadth of their experiments and tests (bench experimentation will be discussed first, followed by pilot testing).

Argonne's Bench-Scale Thermogravimetric & Kinetics Research

DOE's Argonne National Laboratory is carrying out laboratory experiments aimed at determining the effect of different operating parameters on reaction product composition and deriving an analytical model of the pyrolytic process that describes chemical kinetics. Argonne has determined the pyrolytic reactivity for some of the components of MSW in a non-isothermal thermogravimetric analyzer (TGA) and bench-scale reactor (see Figure 7). Typically, the effects of heating rate and sample weight on overall degradation and on product formation over the temperature range of 300 to 475°C were determined. This temperature range was chosen so that the formation of liquid products from the pyrolysis could be emphasized. Research to develop a kinetic model to describe the the decomposition of various cellulosic materials is also underway.[13,14]

University of Arizona's "Liquefaction of MSW in an Autoclave" Research

DOE carried out a one-year exploratory research project at the University of Arizona aimed at studying the fundamentals of direct liquefaction of individual MSW components in a semi-continuous, stirred autoclave. Feedstocks included α-cellulose, lignin, wood flour, cardboard, newsprint and rice (starch). It was found that these MSW constituents could be converted to liquid oils and a residual solid having a high heating value at temperatures of 325 to 400°C and pressures of 1000 to 3000 psi. The carbon content of the product oils varied from 61 to 81 percent, however the hydrogen content remained relatively constant. The heating value correlated to some extent with the oxygen content, varying from about 13,000 to 17,000 Btu/lb.

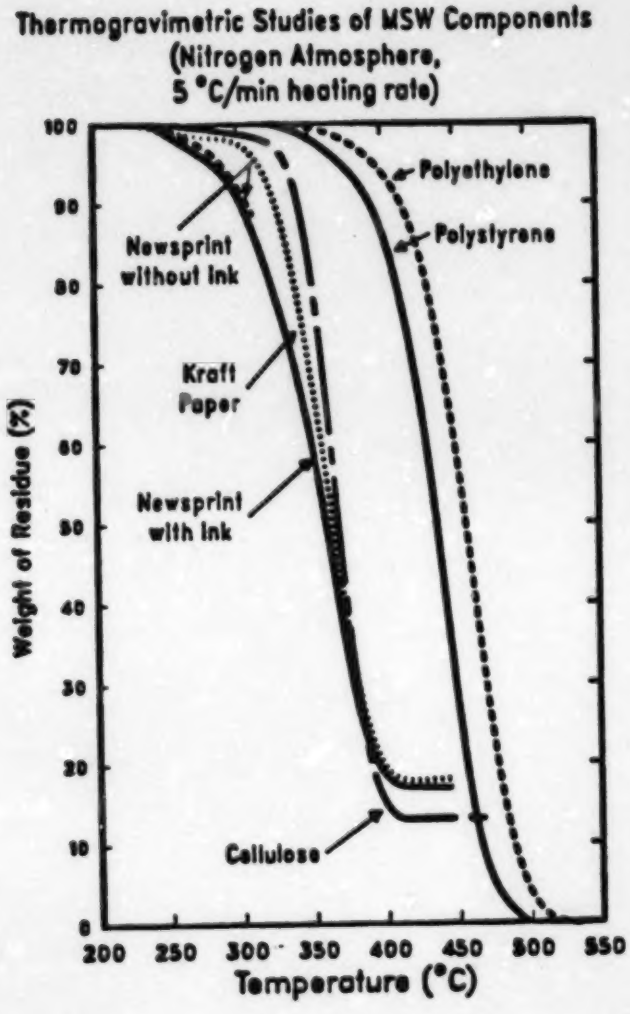

Figure 7. Thermogravimetric Studies of MSW Components (Argonne)

Generally, the oxygen content was found to vary inversely with reaction temperature. Consequently, the oils produced at the lower liquefaction temperatures normally contain more oxygen and have lower heating values.[15]

SERI's "Atlas of Primary Pyrolysis Products" Research

SERI, the Solar Energy Research Institute, operated for DOE by the Midwest Research Institute, has produced an "atlas" of MSW primary pyrolysis products by using a "flame-pyrolysis," high-pressure, molecular-beam, mass spectrometer sampling technique to "fingerprint" the various constituents. In addition, further studies have been carried out in which the influence of sample properties and reaction conditions (such as sample size, temperature, moisture content and reaction time) have been investigated.[16,17,18]

Brookhaven's "Flash Pyrolysis with Methane" Research

DOE's Brookhaven National Laboratory (BNL) is involved in studying a very rapid ("flash") pyrolysis technique at the bench-scale. BNL is investigating the flash pyrolysis of wood using methane as the pyrolysis gas ("methanolysis") in a 1-inch diameter, entrained-flow 8-foot long tubular reactor that operates from 850 to 1000°C (and normally at 50 psi) in a downflow mode (300- to 1000-micron wood particles are fed to the top of the reactor). The product yields consist mainly of ethylene, ethane, benzene, toluene, xylene (BTX) and carbon monoxide. For pure wood at 1000°C and 50 psi, the yield of ethylene has been found to be 8 times higher with methane gas than with helium. Figure 8 shows the percentage of carbon converted to hydrocarbons (HC) versus reactor temperature for the flash methanolysis of pine at 50 psi with a wood particle residence time of 1.1 to 1.3 seconds.[18]

Battelle-Northwest's Bench-Scale "Biomass Catalytic Gasification" Research

DOE's Pacific Northwest Laboratory (PNL), operated by the Battelle Memorial Institute, is engaged in doing bench-scale research on the catalytic conversion of biomass to various gas products.[18,19] They have studied the use of K_2CO_3 and Na_2CO_3 as primary gasification catalysts, and the use of NiCuMo on silica alumina and Ni on α-alumina for the secondary catalysis of wood to synthesis gas. Figure 9 presents a schematic of the 2-stage catalytic system used. It was found that if the primary and secondary stages of catalysis are, in fact, kept physically apart in separate reactors, and if the secondary stage is operated as a fluid bed, then the secondary catalyst will not be deactivated (compared to processing schemes where the secondary catalyst is either mixed with bed material of the primary gasifier or kept in a separate, fixed-bed arrangement).[18] The major cause of secondary catalyst deactivation was therefore attributed to carbon deposition, which the inter-stage char filters and the violent action of the fluid bed basically eliminates.

SERI's "Catalytic Upgrading of Oxygenated Pyrolysis Oils" Research

DOE's Solar Energy Research Institute (SERI) is carrying out bench-scale research on the low-pressure (non-hydrogenation) catalytic upgrading of

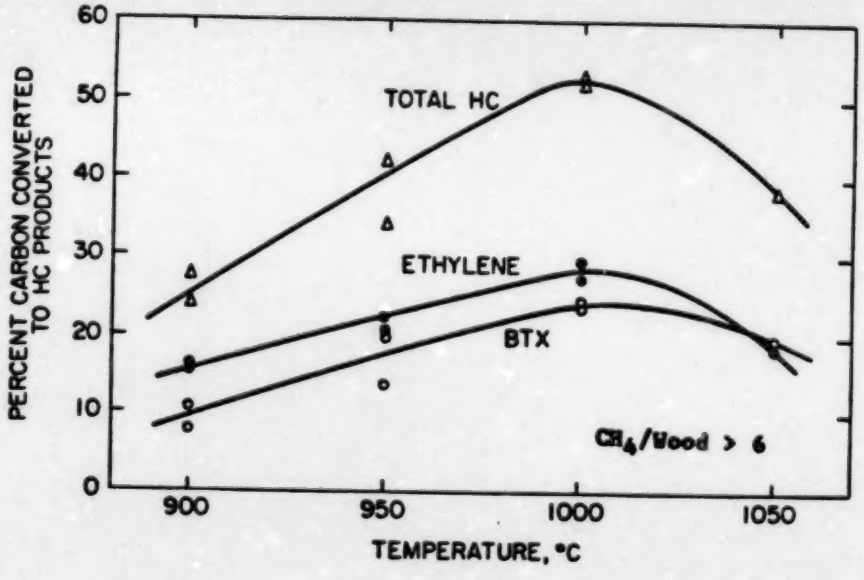

Figure 8. Flash Methanolysis of Pine at 50 psi (Brookhaven)

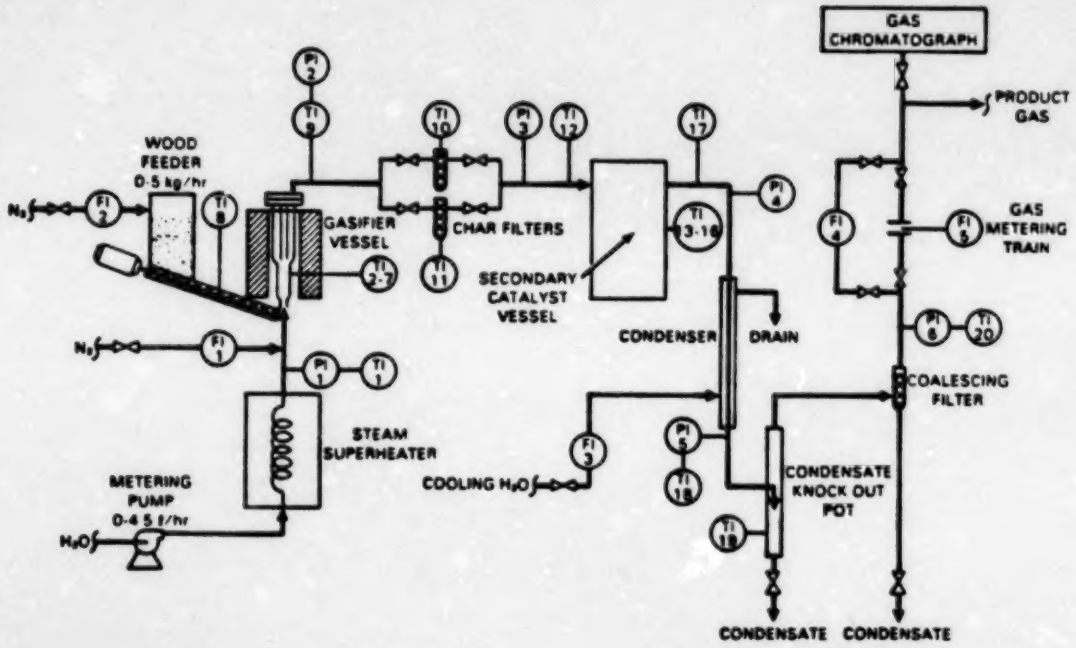

Figure 9. Schematic of 2-Stage Catalytic System (Battelle-Northwest)

pyrolysis oil vapors derived from biomass feedstocks to either a high-octane gasoline or a high-octane blending component.[18,20] Mobil's ZSM-5 zeolite catalyst has been tested and found to be very reactive with oil vapors derived from cellulose, but much less so with lignin-derived oil vapors. A visual representation of the former phenomena is shown in Figure 10, which shows that use of the ZSM-5 catalyst did convert pyrolysis off-gases to partially deoxygenated and other new hydrocarbon products.[18]

Georgia Tech's Pilot-Scale "Entrained-Flow Pyrolysis of Biomass" Research

The Georgia Tech Research Institute is carrying out a research effort for DOE which is aimed at optimizing the oil yield from the entrained-flow pyrolysis of hardwoods. Georgia Tech has constructed a Process Research Unit (PRU) which now features a 6-inch inside diameter reactor tube (down from an originally tested 8-inch diameter one); it is shown schematically in Figure 11. In preliminary tests using the new reactor size, reactor temperatures were varied from 458°C to 527°C. Oil yields were maximum at 477°C where they averaged about 50.7% of the input feed (on a dry basis). At the other temperatures, the oil yields ranged from 37 to 49%.[18]

IGT's Pilot-Scale "12 TPD Biomass Gasifier" Research

The Institute of Gas Technology (IGT) is testing for the DOE a 12 TPD (ton-per-day) process research unit (PRU) to optimize an "oxygen-blown" process for the production of medium-Btu (about 300 to 400 Btu/scf) gas which is suitable for use as industrial fuel gas or for upgrading to substitute natural gas (SNG) or suitable for use as a synthesis gas (syngas). Overall gasification performance has been measured as a function of reactor temperature and pressure, feed rate, steam-to-biomass ratio, type of feedstock, feed moisture, and fluidized bed height. Test results indicate that carbon conversions of about 95% can be achieved with thermal efficiencies of about 75% and with low oil and tar production. Figure 12 presents the effect of reactor temperature on product gas composition.[18]

SERI's Pilot-Scale "20 TPD Moving-Bed Gasifier" Research

SERI, DOE's Solar Energy Research Institute, is also involved in trying to advance biomass pyrolysis or gasification research by operating and testing a 20 TPD moving-bed, down-draft gasifier. Under a sub-contract to Syn-Gas Incorporated (SGI), SERI is testing both an air-fed and an oxygen-fed gasifier mode of operation. In addition, an upflow configuration is being investigated. Sub-pilot tests are also being conducted to guide the larger, pilot-scale PRU tests.[18] A schematic diagram of the SGI Down-Draft Gasifier is shown in Figure 13.[6]

University of Missouri at Rolla's "6 TPD Indirect-Fired Fluid Bed Gasifier" Research

The University of Missouri (at Rolla, Missouri) is determining the feasibility of using an internal heat exchanger to provide heat indirectly to a 6 TPD fluidized bed gasifier.[6] The gas produced is a medium-Btu gas, varying from 350 to 550 Btu/scf. Instead of using oxygen to achieve this

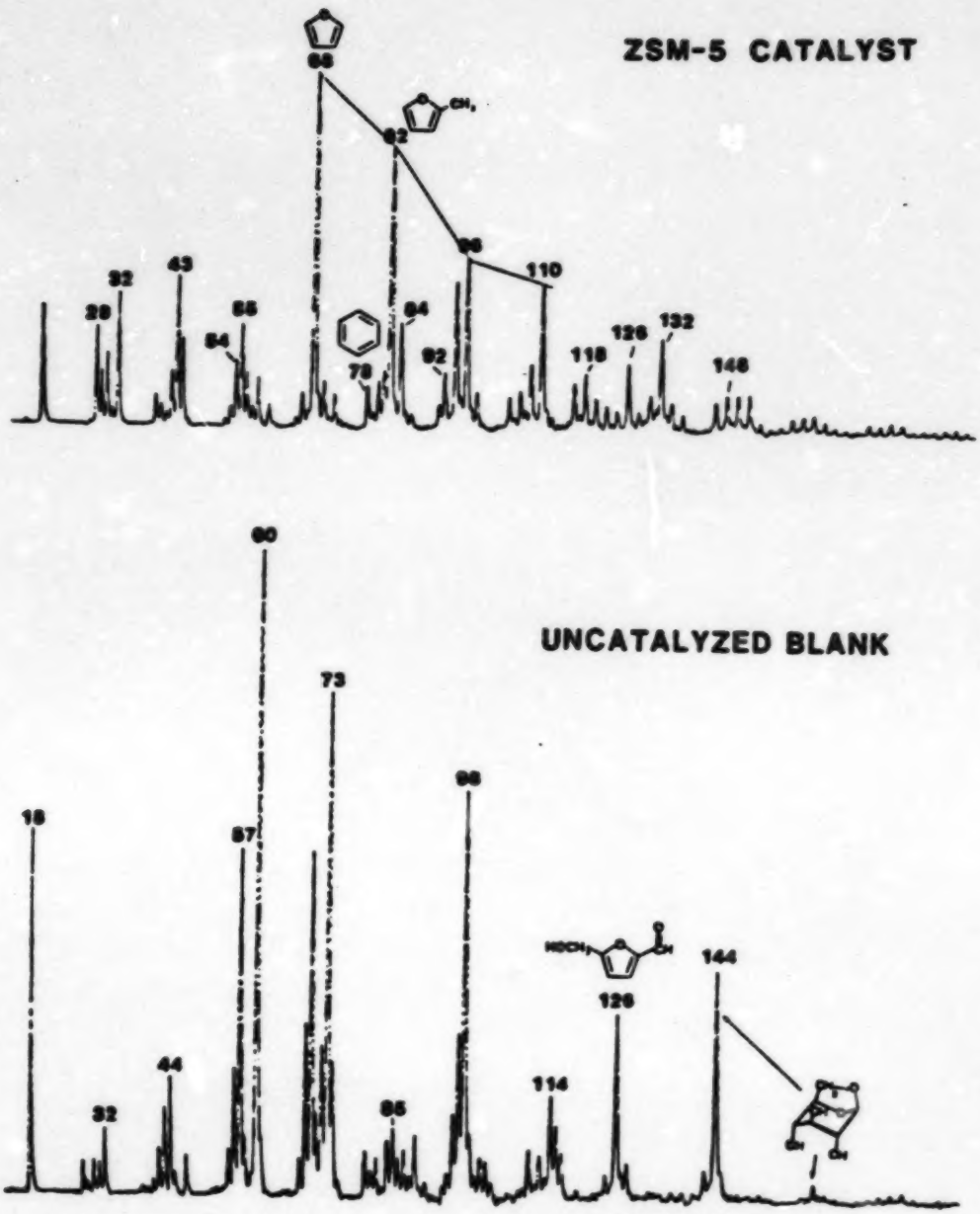

Figure 10. Mass Spectra of the Effect of Zeolite Catalyst on Cellulose-Derived Vapors (SERI)

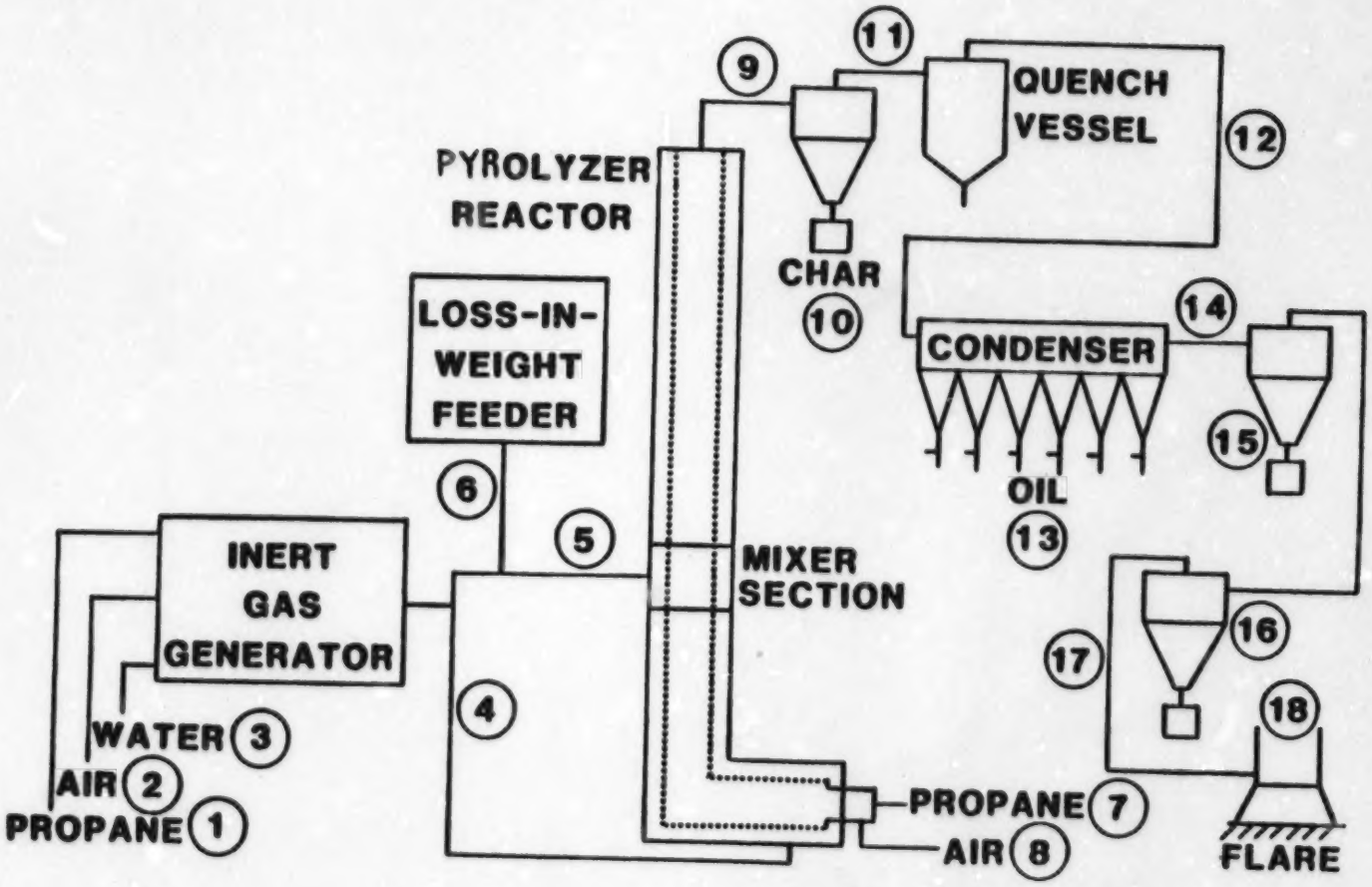

Figure 11. Flow Diagram of the Process Research Unit at Georgia Tech

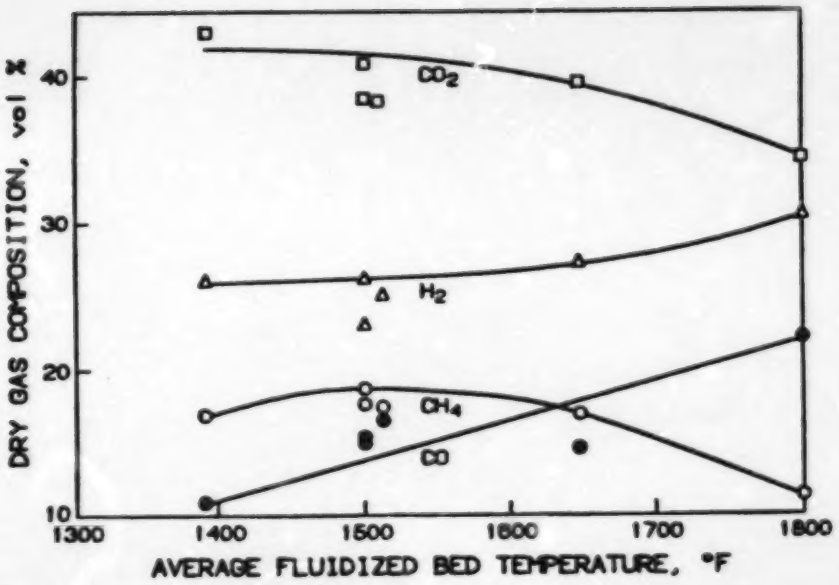

Figure 12. Effect of Gasification Temperature on Product Gas Composition (IGT)

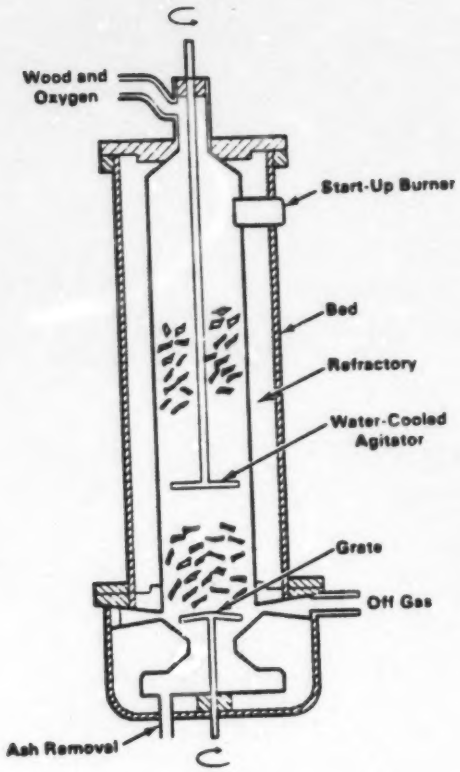

Figure 13. Schematic Diagram of the SGI Down-Draft Gasifier(SERI)

relatively high heating value of the product gas, this pilot-scale system uses a tube bundle consisting of 30 one-inch diameter U-tubes that have propane combustion off-gases going through them. These tubes then provide indirect heat to the fluidized bed of wood waste or biomass that is gasified around the outside of the tubes. Figure 14 provides a schematic of the gasifier used. The unit has been operated for over 8000 hours, with continuous operation lasting for up to 5 days, 24 hours per day.[18]

Battelle-Columbus' Pilot-Scale "12 TPD Non-Oxygen Gasifier to a Methane-Rich Product Gas" Research

The Columbus (Ohio) Division of Battelle is testing for DOE a pilot unit that produces a medium-Btu gas (450-500 Btu/scf) also without the use of oxygen. It uses a dual bed, entrained gasifier that provides for the indirect heating of the gasifier (typically fed wood in these tests) by circulating a low density, hot, incandescent sand from a combustor to the gasifier, as depicted in Figure 15. The entrained sand and any char leaving the gasifier is separated from the product gas in a cyclone separator. These materials are then sent to the bottom of the entrained bed combustor where the char is burned off with air. The sand is thereby heated to a high temperature and then recirculated back of the bottom of the gasifier.[6] Battelle researchers feel that the application of this technology to MSW (municipal solid waste) would also be quite promising.[18]

NEW COMMERCIAL PLANTS ON THE HORIZON

As can be seen from the above, there are many pyrolysis processes under bench- and pilot-scale development. As these mature and the operational difficulties associated with them are overcome, and as they become more economically competitive with conventional waste disposal or energy production technologies, waste or biomass pyrolysis technologies will gradually be commercialized. One such commercialization is discussed below.

PRS's "Fluidized Bed Gasification of Derry, New Hampshire's MSW" Project

Power Recovery Systems, Incorporated (PRS) is beginning work to design and build a 400 TPD (ton-per-day) fluidized bed gasification plant to convert MSW (municipal solid waste) from the Town of Derry, New Hampshire into electric energy. Figure 16 presents a schematic of the PRS Fluidized Bed Gasification System.[21] The PRS technology typically provides for the recovery of recyclable materials (ferrous metals, aluminum, glass, etc.) and produces a low-Btu gas (of about 150 to 200 Btu/scf) whose primary energy constituents are H_2, CO and CH_4.[21,22] The low-Btu gas can then be used in various ways to produce energy: as a boiler fuel, as a fuel for process heating, and as a fuel for internal combustion engines.

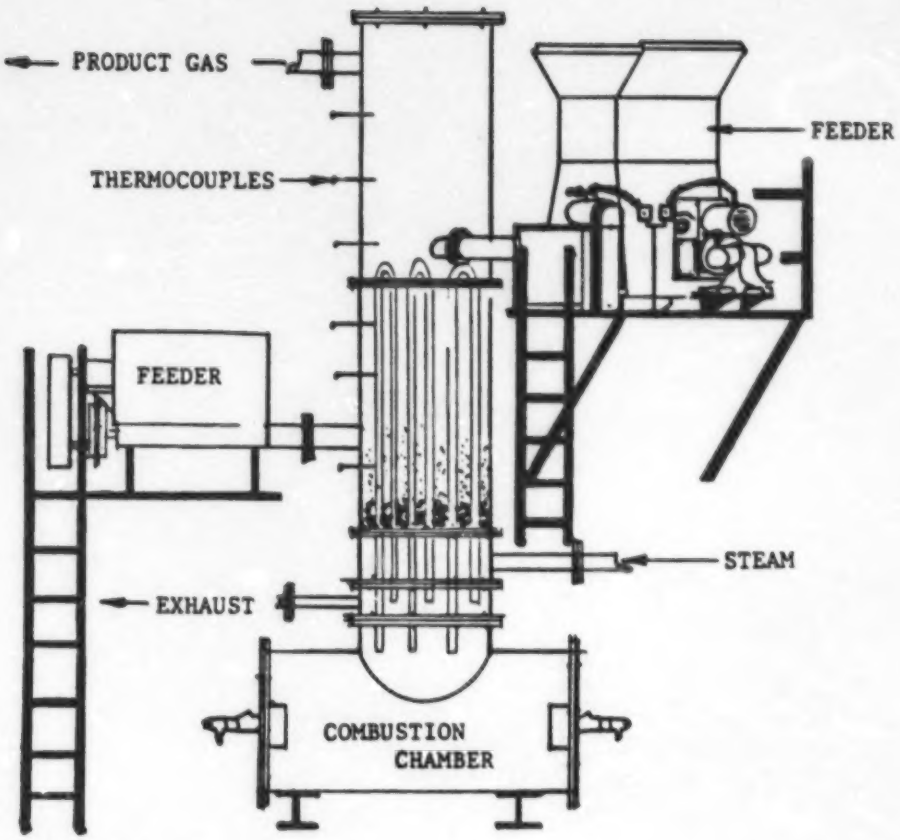

Figure 14. Schematic of 6 TPD Indirect-Fired Fluid Bed Gasifier (University of Missouri at Rolla)

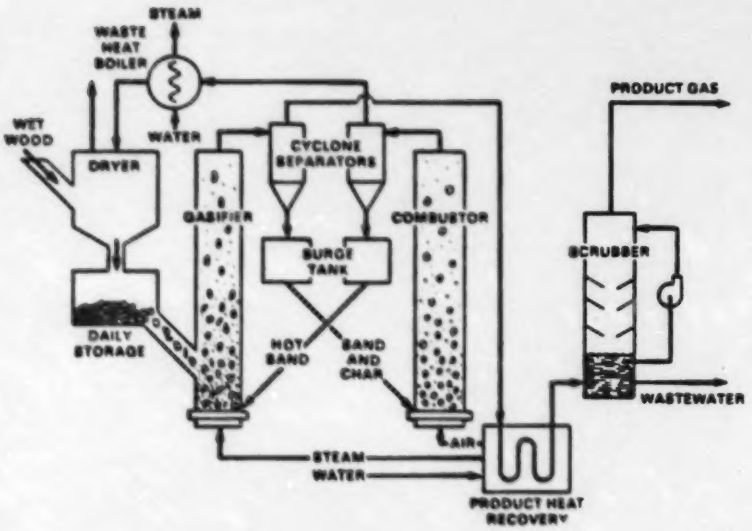

Figure 15. Schematic Diagram of Battelle-Columbus Gasifier

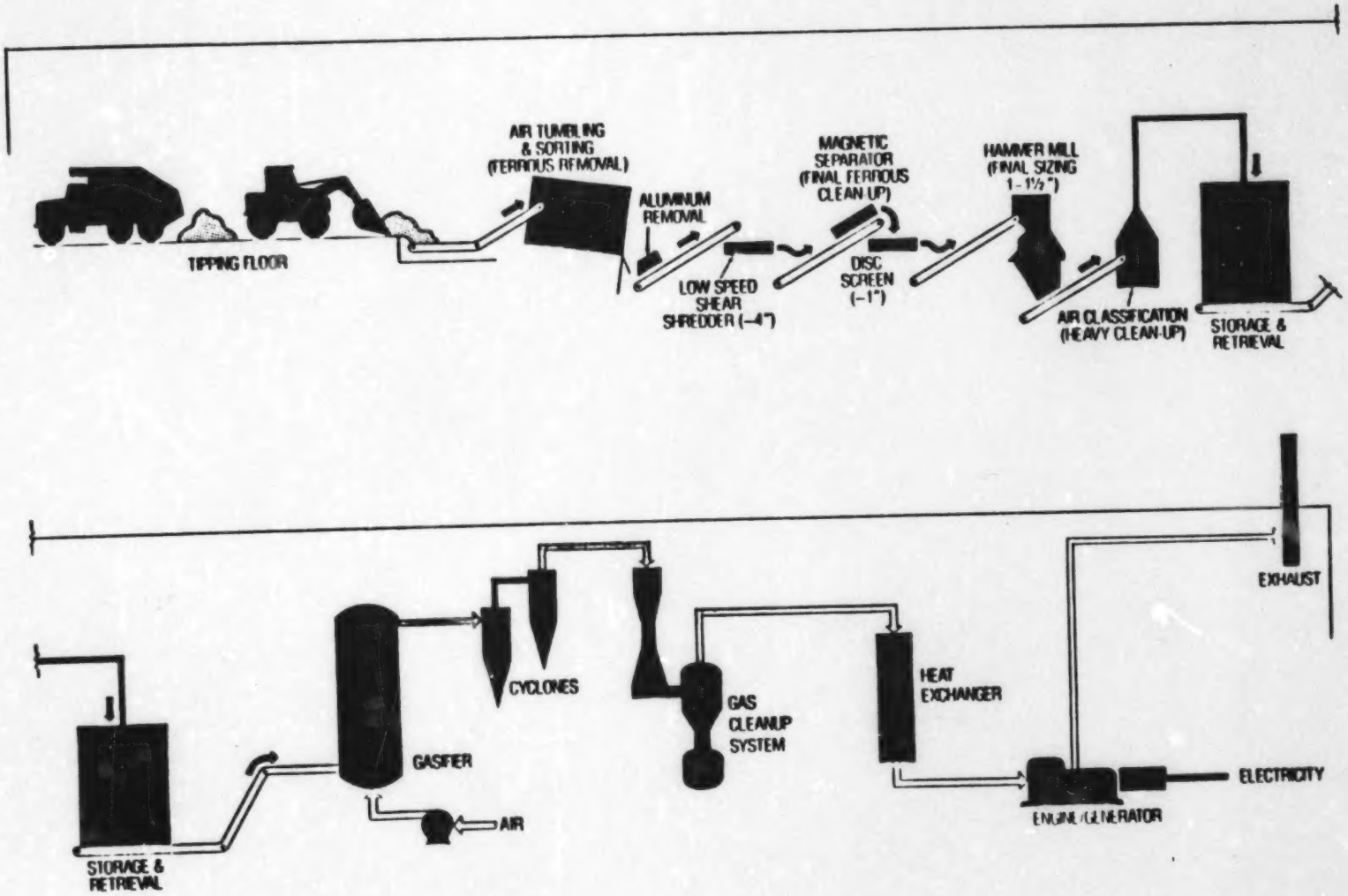

Figure 16. Schematic of the Power Recovery Systems, Inc. Fluidized Bed Gasification Process

CONCLUSION

There are various pyrolysis processes that have been under development for recovering energy from municipal and industrial wastes and from various biomass feedstocks. These developments have been underway under the sponsorship of both the U.S. Government and U.S. industries; however, this Paper has emphasized primarily the Government research that has been carried out. In fact, of the 21 pyrolysis processes/projects discussed herein, 19 were Government-sponsored ones (7 by EPA and 12 by DOE) and 2 were developed by industry (Union Carbide and Power Recovery Systems).

This Paper represents a Historical Overview of U.S. research and development activities associated with waste and biomass conversion-to-energy pyrolysis technologies. It covers the period from 1970 to 1986.

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